Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number

13-SAT13-0018

NASA PROCEDURE FOR HANDLING PROPOSALS

This proposal shall be used and disclosed for evaluation purposes only, and a copy of this Government notice shall be applied to any reproduction or abstract thereof. Any authorized restrictive notices that the submitter places on this proposal shall also be strictly complied with. Disclosure of this proposal for any reason outside the Government evaluation purposes shall be made only to the extent authorized by the Government.

SECTION I - Proposal Information

Principal Investigator	E-mail Address	Phone Number
Richard Lyon	**Richard.G.Lyon@nasa.gov**	**301-286-4302**

Street Address (1)	Street Address (2)
Greenbelt Road	**606.3**

City	State / Province	Postal Code	Country Code
Greenbelt	**MD**	**20771**	**US**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

Proposed Start Date	Proposed End Date	Total Budget	Year 1 Budget	Year 2 Budget	Year 3 Budget
10 / 01 / 2014	**09 / 30 / 2016**	**393,343.00**	**193,936.00**	**199,407.00**	**0.00**

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NNH13ZDA001N-SAT	**Strategic Astrophysics Technology**

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*

NASA , Headquarters , Science Mission Directorate , Astrophysics

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
03 / 21 / 2014	**Electronic Submission Only**		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
004968611	**36FC1**	**520734375**	**2A**

Organization Name (Standard/Legal Name)	Company Division
NASA Goddard Space Flight Center	

Organization DBA Name	Division Number
NASA	

Street Address (1)	Street Address (2)
8800 GREENBELT RD	

City	State / Province	Postal Code	Country Code
GREENBELT	**MD**	**20771-2400**	**USA**

SECTION IV - Proposal Point of Contact Information

Name	Email Address	Phone Number
Richard Lyon	**Richard.G.Lyon@nasa.gov**	**301-286-4302**

SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in this solicitation.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
David Leisawitz	**David.T.Leisawitz@nasa.gov**	**301-286-0807**

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)* **Date**

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**
Proposal Title : **Segmented Aperture Nulling Coronagraphy**	

SECTION VI - Team Members

Team Member Role	Team Member Name	Contact Phone	E-mail Address
PI	**Richard Lyon**	**301-286-4302**	**Richard.G.Lyon@nasa.gov**
Organization/Business Relationship: **NASA Goddard Space Flight Center**		Cage Code: **36FC1**	DUNS#: **004968611**
International Participation: **No**	U.S. Government Agency: **NASA Goddard Space Flight Center**		Total Funds Requested: **0.00**
Co-I	**Matthew Bolcar**	**301-286-5237**	**matthew.bolcar@nasa.gov**
Organization/Business Relationship: **NASA Goddard Space Flight Center**		Cage Code: **36FC1**	DUNS#: **004968611**
International Participation: **No**	U.S. Government Agency: **NASA Goddard Space Flight Center**		Total Funds Requested: **0.00**
Co-I	**Mark Clampin**	**301-286-4532**	**mark.clampin@nasa.gov**
Organization/Business Relationship: **NASA Goddard Space Flight Center**		Cage Code: **36FC1**	DUNS#: **004968611**
International Participation: **No**	U.S. Government Agency: **NASA Goddard Space Flight Center**		Total Funds Requested: **0.00**
Co-I	**Peter Petrone**	**301-286-8881**	**PPetrone@sigmaspace.com**
Organization/Business Relationship: **Sigma Space Corporation**		Cage Code: **1MRJ5**	DUNS#: **047601294**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**Kenneth Carpenter**	**301-286-3453**	**Kenneth.G.Carpenter@nasa.gov**
Organization/Business Relationship: **NASA Goddard Space Flight Center**		Cage Code: **36FC1**	DUNS#: **004968611**
International Participation: **No**	U.S. Government Agency: **NASA Goddard Space Flight Center**		Total Funds Requested: **0.00**
Postdoctoral Associate	**Brian Hicks**	**301-286-1927**	**brian.a.hicks@nasa.gov**
Organization/Business Relationship: **NASA Goddard Space Flight Center**		Cage Code: **36FC1**	DUNS#: **004968611**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**

PI Name : **Richard Lyon**	**NASA Proposal Number**
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION VII - Project Summary

Future large aperture exoplanet coronagraphic instruments may be limited to segmented apertures or apertures on an existing mission and thereby must conform to the telescope as is. This is significantly different than most past proposed coronagraphic approaches that often require a filled unobscured aperture with no diffracting structure. The Visible Nulling Coronagraph (VNC) in principle works with arbitrary apertures. The VNC has been developed and significantly advanced by our team. Herein we propose to demonstrate, and quantify, high contrast imaging with a segmented aperture using an existing reconfigurable segmented telescope feeding into our existing VNC.

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION VIII - Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?

Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?

No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	**No**	**No**	**No**	**No**

Explanation :

NASA Civil Servant Project Personnel

Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)?

Yes

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
2015	**2016**				
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs
0.8	**0.8**				

PI Name : **Richard Lyon**	**NASA Proposal Number**
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION VIII - Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment?	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed?
No	**No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

PI Name : **Richard Lyon**	**NASA Proposal Number**
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION VIII - Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION IX - Program Specific Data

Question 1 : Short Title:

Answer: Segmented Aperture Nulling Coronagraphy

Question 2 : Type of institution:

Answer: NASA Center (including JPL)

Question 3 : Will any funding be provided to a federal government organization including NASA Centers, JPL, other Federal agencies, government laboratories, or Federally Funded Research and Development Centers (FFRDCs)?

Answer: Yes

Question 4 : Is this Federal government organization a different organization from the proposing (PI) organization?

Answer: No

Question 5 : Does this proposal include the use of NASA-provided high end computing?

Answer: No

Question 6 : Research Category:

Answer: 4) Instrument development (includes basic/advanced space and suborbital Instrumentation)

Question 7 : Team Members Missing From Cover Page:

Answer:

Question 8 : This proposal contains information and/or data that are subject to U.S. export control laws and regulations including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR).

Answer: No

Question 9 : I have identified the export-controlled material in this proposal.

Answer: N/A

Question 10 : I acknowledge that the inclusion of such material in this proposal may complicate the government's ability to evaluate the proposal.

Answer: N/A

Question 11 : Does the proposed work include any involvement with collaborators in China or with Chinese organizations, or does the proposed work include activities in China?

Answer: No

Question 12 : Are you planning for undergraduate students to be involved in the conduct of the proposed investigation?

Answer: Yes

Question 13 : If yes, how many different undergraduate students?

Answer: 2

Question 14 : What is the total number of student-months of involvement for all undergraduate students over the life of the proposed investigation?

Answer: 8

Question 15 : Provide the names and current year (1,2,3,4) for any undergraduate students that have already been identified.

Answer:

none.

Question 16 : Are you planning for graduate students to be involved in the conduct of the proposed investigation?

Answer: No

Question 17 : If yes, how many different graduate students?

Answer: N/A

Question 18 : What is the total number of student-months of involvement for all graduate students over the life of the proposed investigation?

Answer: 0

Question 19 : Provide the names and current year (1,2,3,4, etc.) for any graduate students that have already been identified.

Answer:

none

Question 20 : Type of Proposal:

Answer: Technology Development for Exoplanet Missions (TDEM)

Question 21 : TDEM Area of Emphasis:

Answer: System Performance Assessment

Question 22 : TPCOS Area of Emphasis:

Answer:

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Cumulative Budget

Budget Cost Category	Funds Requested ($)			
	Year 1 ($)	Year 2 ($)	Year 3 ($)	Total Project ($)
A. Direct Labor - Key Personnel	0.00	0.00	0.00	0.00
B. Direct Labor - Other Personnel	113,640.00	149,722.00	0.00	263,362.00
Total Number Other Personnel	3	4	0	7
Total Direct Labor Costs (A+B)	113,640.00	149,722.00	0.00	263,362.00
C. Direct Costs - Equipment	0.00	0.00	0.00	0.00
D. Direct Costs - Travel	0.00	7,676.00	0.00	7,676.00
Domestic Travel	0.00	7,676.00	0.00	7,676.00
Foreign Travel	0.00	0.00	0.00	0.00
E. Direct Costs - Participant/Trainee Support Costs	0.00	0.00	0.00	0.00
Tuition/Fees/Health Insurance	0.00	0.00	0.00	0.00
Stipends	0.00	0.00	0.00	0.00
Travel	0.00	0.00	0.00	0.00
Subsistence	0.00	0.00	0.00	0.00
Other	0.00	0.00	0.00	0.00
Number of Participants/Trainees				0
F. Other Direct Costs	80,296.00	42,009.00	0.00	122,305.00
Materials and Supplies	54,100.00	15,000.00	0.00	69,100.00
Publication Costs	0.00	0.00	0.00	0.00
Consultant Services	0.00	0.00	0.00	0.00
ADP/Computer Services	0.00	0.00	0.00	0.00
Subawards/Consortium/Contractual Costs	0.00	0.00	0.00	0.00
Equipment or Facility Rental/User Fees	0.00	0.00	0.00	0.00
Alterations and Renovations	0.00	0.00	0.00	0.00
Other	26,196.00	27,009.00	0.00	53,205.00
G. Total Direct Costs (A+B+C+D+E+F)	193,936.00	199,407.00	0.00	393,343.00
H. Indirect Costs	0.00	0.00	0.00	0.00
I. Total Direct and Indirect Costs (G+H)	193,936.00	199,407.00	0.00	393,343.00
J. Fee	0.00	0.00	0.00	0.00
K. Total Cost (I+J)	193,936.00	199,407.00	0.00	393,343.00
Total Cumulative Budget				393,343.00

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2014	**09 / 30 / 2015**	**Project**	**1**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Lyon, Richard	**PI**	**0.00**	**6**			**0.00**	**0.00**	**0.00**
Clampin, Mark	**CO-I**	**0.00**	**.6**			**0.00**	**0.00**	**0.00**
Bolcar, Matthew	**CO-I**	**0.00**	**3.6**			**0.00**	**0.00**	**0.00**
							Total Key Personnel Costs	**0.00**

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
1	**Engineer-Sr**	**9**			**90,000.00**	**0.00**	**90,000.00**
1	**(CS)Technician-Mid**	**.49**			**0.00**	**0.00**	**0.00**
1	**Technician-Mid**	**.49**			**23,640.00**	**0.00**	**23,640.00**
3	**Total Number Other Personnel**					**Total Other Personnel Costs**	**113,640.00**
						Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	**113,640.00**

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2014	**09 / 30 / 2015**	**Project**	**1**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**0.00**
2. Foreign Travel	**0.00**
Total Travel Costs	**0.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2014	**09 / 30 / 2015**	**Project**	**1**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	54,100.00
2. Publication Costs	0.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
8 . Other: **SED - Other Direct Support**	26,196.00
Total Other Direct Costs	80,296.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	193,936.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Cognizant Federal Agency:		**Total Indirect Costs**	0.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	193,936.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	193,936.00

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2015	**09 / 30 / 2016**	**Project**	**2**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Clampin, Mark	CO-I	0.00	.6			0.00	0.00	0.00
Lyon, Richard	PI	0.00	6			0.00	0.00	0.00
Bolcar, Matthew	CO-I	0.00	3.24			0.00	0.00	0.00
							Total Key Personnel Costs	0.00

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
1	Engineer-Sr	6			92,700.00	0.00	92,700.00
1	Scientist-Tier 1	3.96			40,788.00	0.00	40,788.00
1	(CS)Technician-Mid	.33			0.00	0.00	0.00
1	Technician-Mid	.33			16,234.00	0.00	16,234.00
4	Total Number Other Personnel					Total Other Personnel Costs	149,722.00
						Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	149,722.00

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2015	**09 / 30 / 2016**	**Project**	**2**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**7,676.00**
2. Foreign Travel	**0.00**
Total Travel Costs	**7,676.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
10 / 01 / 2015	09 / 30 / 2016	Project	2

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	15,000.00
2. Publication Costs	0.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
8 . Other: SED - Other Direct Support	27,009.00
Total Other Direct Costs	42,009.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	199,407.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Cognizant Federal Agency:		Total Indirect Costs	0.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	199,407.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	199,407.00

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**
Proposal Title : **Segmented Aperture Nulling Coronagraphy**	

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
		Project	**3**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Lyon, Richard	**PI**	**0.00**				**0.00**	**0.00**	**0.00**
							Total Key Personnel Costs	**0.00**

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
0	Total Number Other Personnel					Total Other Personnel Costs	**0.00**
						Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	**0.00**

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
		Project	**3**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	0.00

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	0.00
2. Foreign Travel	0.00
Total Travel Costs	0.00

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		0.00
2. Stipends		0.00
3. Travel		0.00
4. Subsistence		0.00
Number of Participants/Trainees:	Total Participant/Trainee Support Costs	0.00

PI Name : **Richard Lyon**	NASA Proposal Number
Organization Name : **NASA Goddard Space Flight Center**	**13-SAT13-0018**

Proposal Title : **Segmented Aperture Nulling Coronagraphy**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
		Project	**3**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	0.00
2. Publication Costs	0.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
Total Other Direct Costs	0.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	0.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Cognizant Federal Agency:		**Total Indirect Costs**	0.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	0.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	0.00

Segmented Aperture Nulling Coronagraphy

Proposer Richard Lyon - NASA/Goddard Space Flight Center

Submitted in response to NNH13ZDA001N-SAT

Table of Contents

Scientific/Technical/Management

1. Executive Summary

Recent successes with the GSFC laboratory visible nulling coronagraph (VNC) has advanced its observed contrast to 5.5 $\times 10^{-9}$ at $2\lambda/D$ inner working angle (IWA) while operating in closed-loop control with a segmented deformable mirror (Clampin 2013, Lyon 2012) – *it is the deepest nulling with any interferometer* (Figure-3).

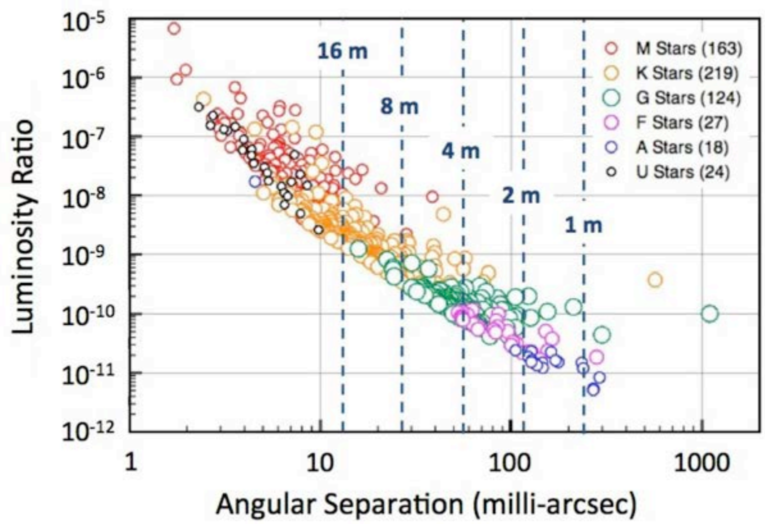

Figure-1: *Candidate terrestrial exoplanet luminosity ratio vs angular separation*. Apertures from 1–16 meters shown as blue dashed lines. Each aperture 'sees' planets to the right of its dashed line assuming 2 λ/D IWA. Plot includes all stars to a distance of 30 parsecs in V-band with an assumed Earth diameter planet in its mean habitable zone. Candidates per spectral class is labeled in the legend (Lyon & Clampin 2012).

The direct detection and characterization of exosolar planets is predicated on having the light gathering power and angular resolution available with large telescopes. It additionally requires the ability to suppress starlight relative to the planet at small angular separations, i.e. coronagraphy. The planet-to-star luminosity ratio in visible light versus angular separation (Figure-1) for candidate target stars out to 30 parsecs shows that smaller apertures (1-2 meter) see few terrestrial planets, even when an Earth diameter terrestrial is assumed in each stars habitable zone (HZ). Thus 4-m or larger apertures are needed. A 4-m may be difficult with regards to science since current Kepler results, i.e. η_{EARTH}, does not guarantee enough targets since it is unlikely that each star system has a terrestrial planet ($\eta_{EARTH} \neq 1$). JWST will be the largest science aperture in space at 6.5-m. It is a deployable segmented aperture telescope designed to image 1st light targets. NASA's investment in JWST will have an impact on telescope architectures for future flight missions. Apertures of 8-m, or larger, are most likely to follow the segmented aperture approach. Thus *coronagraphy should be adept at operating on segmented apertures* and the trade space expanded to include segmented-aperture coronagraphy. The VNC permits high contrast coronagraphy at small IWA for arbitrary apertures; developing it also permits high precision coronagraphy on telescopes with less stressing stability (pm) requirements that may be beyond our current ability to build, test and fly.

High contrast imaging at close IWA is not well matched to the diversity of potential flight aperture shapes. Visible nulling is adaptable to a variety of apertures.

This enables trades, for future flight exoplanet missions, encompassing the science, mission architecture, technology and costs.

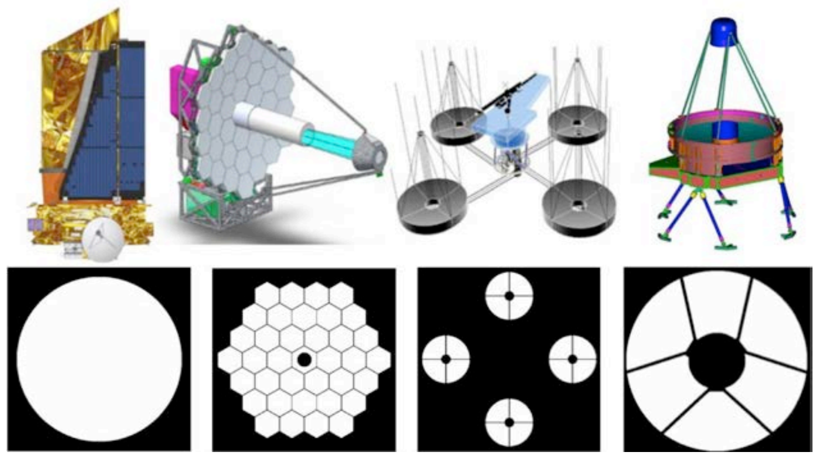

Figure 2: *VNC studies for exoplanet missions that span aperture ranges* EPIC (left) is a 1.65-m Probe Class mission concept to image and characterize exosolar planetary environments (Clampin et al 2006), ATLAST (center-left) and (DAViNCI (center-right) are flagship class mission concepts designed to image and characterize terrestrial planets. SALSO represents the telescopes 'gifted' to NASA that may be suitable for limited exoplanet science. Bottom row shows aperture shapes.

Current exoplanet coronagraphy is not well matched to a segmented aperture since the aperture structure diffracts light away from the center (core) of the point spread function (PSF). This diffracted light, and its scatter, shifts light from the location of the star to the planet and lowers the contrast. Alternatively, a segmented aperture can achieve the same contrast as a filled-aperture but at greater angular separations, or specific focal plane locations; either of which lowers the potential number of targets. Increasingly, the diverse space of possible future flight apertures (Figure-2) is not well matched to the suite of ongoing coronagraphs undergoing significant technology development. While segmented apertures are not ideal for exoplanet coronagraphy it is a path that needs further exploration to be better understood.

The VNC has as one of its key benefit (Table-1) that it is one approach that has been shown to be adaptable to a variety of apertures addressed during the Astrophysics Strategic Mission Concept (ASMC) studies. Three of the ASMC studies included a VNC (Figure-2): EPIC with a filled aperture (Clampin 2006), ATLAST with a segmented (Postman 2009), and DAViNCI with a sparse aperture (Shao 2009). Additionally the VNC has been studied for the SALSO telescope (Lyon 2013) and for balloon-borne missions (Lyon 2012).

Table 1: ***Key Benefits of the VNC***

1)	2 λ/D Inner Working Angles delivers maximum discovery space for a given telescope aperture.
2)	Integrated system provides all output signals for pointing, wavefront sensing & control; no additional optical systems required.
3)	Broadband Wavefront sensing & control using both bright-channel rejected stellar light, and dark leaked speckle. Enables fast convergence to high contrast w/ high-bandwidth control.
4)	Significantly Relaxes observatory stability requirements.
5)	Scales naturally scale to segmented, sparse and filled large aperture telescopes,

Evaluations of segmented apertures, sensing/control, and telescope stability, shows that the VNC leads to a viable and manageable approach for a flight mission (Lyon 2005, Lyon 2012). This led to a Discovery mission proposal (EPIC, Clampin 2006) and further study as an ASMC study. To further evaluate the approach and evaluate sub-system level technologies a VNC laboratory testbed was developed at GSFC and achieved milestones in nulling coronagraphy (Figure-3). Our recent laboratory work with the VNC has achieved repeatable contrasts of 5.5×10^{-9} at an

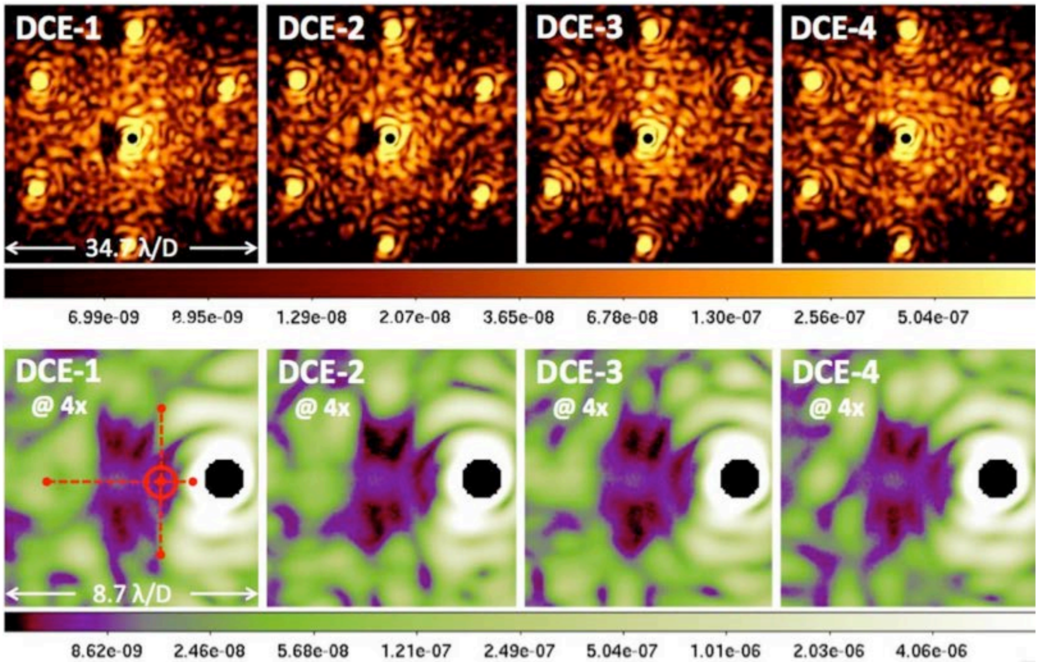

Figure-3: *Contrast Maps*. Top row shows resulting average contrast maps from 4 different data collection events (DCE) on log and color stretched scale to accent residual structure. Bottom row is the same images as the top but zoomed by a factor of 4x and shifted to right, and with a different color map, to accent the dark-hole region. The central core is numerically (dark circle) masked to compress the image dynamic range for display purposes. The open red circle on the lower left panel shows a 1 λ/D diameter masked centered on -2 λ/D – this is the region that the contrast is calculated for this milestone.

IWA of 2 λ/D (Clampin 2013, Lyon 2012) while operating under closed-loop control with a segmented deformable mirror. Unlike other traditional coronagraphs this contrast result was achieved in air demonstrating that high bandwidth control contrast control offered by the VNC is the optimum approach for mitigating telescope stability requirements imposed by traditional coronagraphs. It is the first high contrast demonstration with a segmented deformable mirror (DM), and the deepest known nulling of any interferometer to date. The VNC testbed, as it stands now, has not been coupled to a telescope but exists as a stand alone laboratory testbed for evaluating: nulling coronagraphy, sensing and control, and critical technologies including the deformable mirror (DM), spatial filter array (SFA), and achromatic phase shifter (APS). The size of the dark hole is driven by the number of DM actuators – obtaining larger DMs increases the dark-hole size.

We propose to demonstrate high contrast with a segmented aperture telescope coupled to the VNC.

Herein, we propose to advance the VNC for a segmented aperture telescope by: (i) integrating the existing laboratory VNC with an (ii) existing, but modified, sparse aperture testbed known as the Fizeau Interferometry Testbed (FIT) (Lyon, 2004) used to evaluate wavefront control for the Stellar Imager (SI) mission (Carpenter 2005), and (iii) with an existing fast steering mirror (FSM), with (iv) both an emulated planet and star imaged coronagraphically through it. The proposed effort (Figures 4 & 5), known as SAINT (Segmented Aperture Interferometric Nulling Testbed), culminates in a demonstration of an end-to-end system plus instrument level control, with high contrast imaging. We propose to first achieve a conservative contrast of 10^{-8} at IWA of 4 λ/D and spectral bandpass of 20 nm centered

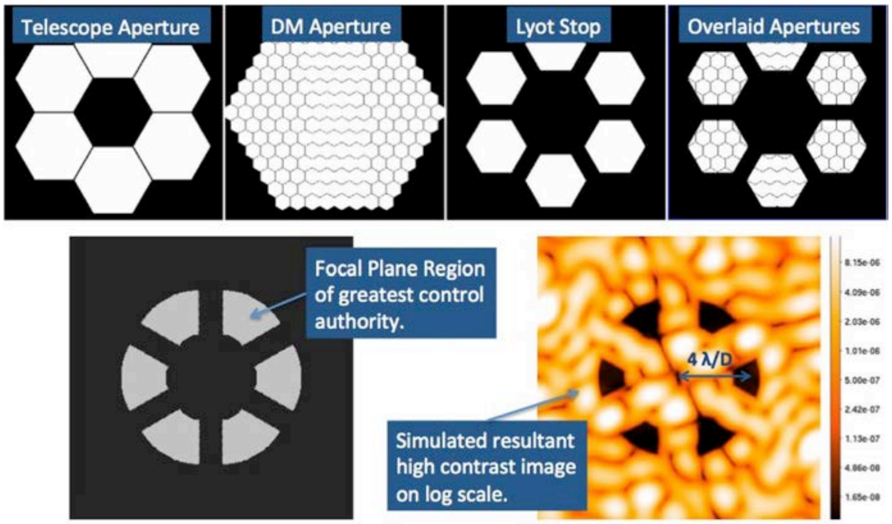

Figure-4: *Simulated High Contrast Imaging through SAINT*. Top row (left-to-right) are: segmented telescope aperture, DM aperture, Lyot stop, and overlay of the three before bringing to focus. Bottom left is the region of the focal plane over which the system control modes are optimized – the light region is where the telescope segments and the DM, after passing through the SFA and APS, works the hardest to suppress. The 6 regions that look like gaps are where the telescope diffraction flairs dominate. Bottom right is a simulated focal plane image at λ = 633 nm, $\Delta\lambda$ = 40 nm with λ/8D camera plate scale. The 6 regions of high contrast are evident but limited by number of DM segments.

on 633 nm (Figure 4 lower right). It is likely that SAINT can reasonably achieve 10^{-9} at a smaller IWA, possibly ~3 λ/D, however we adopt the conservative approach since this is the first time the VNC will have been connected to a segmented aperture; we carry the deeper contrast at smaller IWA as a goal.

Simulations (Figure-4) of wavefront and amplitude control via the DM with SFA show regions of high contrast in the focal plane. Simulations are employed to assess the design and are a component of this effort for sensitivity analysis and error budgeting.

The overall approach is straightforward (shown in block form in Figure-5) and consists of coupling the existing VNC, to a modified version of our existing actuated sparse aperture telescope (previously funded as APRA 2005-2008), modified to accommodate hexagonal rigid body actuated segments, and to install an existing FSM between the telescope and VNC. The

Figure-5: *Block Diagram of Segmented Aperture Interferometric Nulling Testbed (SAINT)*

FSM, and its electronics, are spares from SVIP (Lyon 2004). The FSM operates closed loop at 800 Hz and consists of a ~2 cm flat mounted on actuators from Polytec PI. The existing vacuum tank flange will be modified to incorporate a coated glass window, to allow light from the telescope to enter the vacuum tan and propagate through the VNC.

The VNC consists of a modified Mach-Zehnder interferometer; modified by insertion of a MEMS hexagonal packed segmented deformable mirror (Figure-11), and a spatial filter array based on coherent fiber bundle technology (Lyon 2011), and achromatic phase shifters (Bolcar 2012) to increase the spectral bandpass of the high contrast dark hole and passively control polarization. The VNC, through the use of these technologies, performs fine scale closed-loop wavefront and amplitude control, and passive polarization control over a finite spectral bandpass to null the starlight. The nulled on-axis starlight actually passes through to the wavefront control channel while the off-axis light passes through to the science channel. The coupled control system feeds back: to piston, tip and tilt on each primary mirror (PM) segment of the telescopes; the FSM to stabilize the image (akin to pointing), and feeds back to the hexagonal packed deformable mirror within the VNC. Our approach will demonstrate coupled end-to-end systems and instrument level closed loop control, and demonstrate high contrast imaging through the complete system. Additionally the use of the telescope allows for both a planet and star image within the coronagraph to assess "true" contrast, i.e. not the darkness of a dark hole without the planet signal, but to obtain two images separated by the IWA, one nulled (emulating the on-axis star), and the other un-nulled (emulating the off-axis planet). Contrast is then the ratio of the two signals, i.e. nulled starlight and un-nulled planet light.

The proposed effort completes a key milestone that further advances coronagraphy towards being adaptable to arbitrary apertures, thereby freeing up the necessity of requiring unobscured off-axis telescopes, and takes a significant step towards coronagraphy becoming viable for any telescope. This may result in overall mission cost savings in that either existing telescopes, or telescopes designed and optimized for other science projects, could be made available for exoplanet science missions.

Milestone: The milestone is succinctly stated as *achieve and hold a true contrast of 10^{-8} at an IWA of 4 λ/D within a bandpass of $\Delta\lambda$ = 20 nm for 1,000 seconds on three separate occasions separated by at least 24 hours*, with a goal of 10^{-9} at an IWA of 3 λ/D in a bandpass of $\Delta\lambda$ = 40 nm. The milestone addresses broadband contrast measurement and broadband wavefront control for a segmented aperture. Additionally it measures true contrast, due to the use of two input source beams. Our proposed effort leverages and exploits the lessons learned from completing our SAT/TDEM's first milestone of 10^{-8} contrast at 2 λ/D IWA on 3 separate occasions (Lyon 2012, and to be published TAC report), and of our current ongoing 2nd SAT/TDEM milestone to achieve 10^{-9} at 2 λ/D in 40 nm bandpass on three occasions, and the ongoing SAT/TDEM for environmental testing of MEMS deformable mirrors, additionally for SBIRs for deformable mirrors and spatial filter array advancement.

The milestone is accomplished by modifying our existing sparse aperture testbed to convert it to segmented telescope with reconfigurable aperture patterns, by replacing the circular actuated primary mirror segments with hexagonal packed primary mirror segments. This segmented telescope will have 7 segments comprising a ring of 6 segments and a removable center segment. Each segment is separately mounted on flexure mounted piezo actuators that attach to the back plane structure. This SAINT testbed uses the existing VNC as its science instrument. This would function as a laboratory segmented aperture telescope for low cost since the bulk of these efforts were developed under a previous IRAD, APRA, SAT/TDEM and SBIR efforts, and represents an effective leveraging strategy since primary costs for this effort are to integrate the SAINT and perform the contrast measurements

The milestone proposed herein represents a feasible objective, and, are based on current VNC TRL levels, and TRL levels of wavefront control for segmented apertures (per JWST), and on TRL levels of the component level technologies including the DM, SFA and APS. The proposed effort is an important step towards enabling exoplanet coronagraphy for segmented apertures and ultimately for future missions such as ATLAST or DAViNCI. Upon completion of this two-year effort, sub-system technology will be properly positioned to address the additional steps required to mature this high contrast imaging approach to TRL-6.

Achievement of the proposed milestone to further mature the VNC technique for segmented apertures is important, since the VNC offers key performance benefits when compared to traditional mask based coronagraphs. These make it a natural choice for segmented, and other, aperture systems.

Unlike traditional coronagraphs, the VNC is a single aperture interferometer. A detailed explanation of the VNC's operational concept is presented in Lyon (2005) and Clampin (2006 & 2011). Our team has extensive experience with flight hardware that has flown, or will fly, on SMEX, Spitzer, HST, and JWST. Thus, we have a deep appreciation of the "systems-level" considerations needed to fly an exoplanet-imaging mission.

Our team has the facilities and software tools required to successfully complete this effort. We will utilize several facilities at GSFC, including the VNC testbed facility. The testbed is operational and actively nulling under closed-loop control within the tank. The first VNC TDEM milestone has been achieved and reviewed by the Technical Advisory Committee (TAC). Additionally the MEMS deformable mirror (DM) has been procured via the NASA Small Business Innovation Research (SBIR) awards. A separate null-control breadboard (NCB) is used to develop and test mirror control algorithms. Fiber based spatial filter arrays have been developed and tested, and a phase-II SBIR is ongoing to develop a custom waveguide spatial filter array

The key points (Table-1) are that the VNC delivers excellent science performance, coupled with a design that naturally lends itself to a systems friendly implementation. Perhaps most importantly, the VNC employs both the bright rejected starlight and the dark leaked speckle to sense and control broadband wavefront and amplitude errors as it nulls to the desired contrast level. Traditional coronagraphs as they near the desired contrast are wavefront sensing on an extremely faint, high contrast image, and may require long integration times – hence high system level stability. Completing our milestones in this proposal matures the VNC to the point where it can inform future NASA decisions on technology development and system architectures for NASA exoplanet missions.

2. Technical Approach and Methodology

2.1 Motivation

KEY to Figure-6	
Black lines:	Optical paths.
Magenta dashed:	Auxiliary optical paths.
Blue font:	Electronics associated w/ control system.
Blue solid lines:	Control lines from controller to device.
Blue dashed lines:	Data paths from cameras to control computer.
Green components:	Procured and operational under other efforts.
Red Components:	To be procured under this effort.
Note:	Auxiliary path from removing flip mirror #1 and inserting it at flip mirror #2.

Direct exoplanet imaging with a segmented aperture requires an end-to-end system to evaluate it and we are proposing such a system, i.e. SAINT (Figure-6), along with testing of SAINT to achieve a broadband contrast milestone. Coronagraphy with segmented apertures requires the capability for closed-loop control to mitigate the effects of vibration and thermal drifts of the segmented PM. The primary goal is to complete the SAINT and demonstrate the key contrast milestone to further mature VNC technology towards segmented apertures, The proposed milestones to be demonstrated address the areas of Broadband Starlight Suppression Demonstration, Broadband Wavefront Sensing and Control (WFSC), Advanced Optics and System Performance Assessment.

2.2 SAINT Testbed

Figure-6 is a layout (not to scale) of the SAINT architecture. SAINT consists of 16' x 4' stabilized air table with the source module, segmented aperture telescope, and vacuum tank

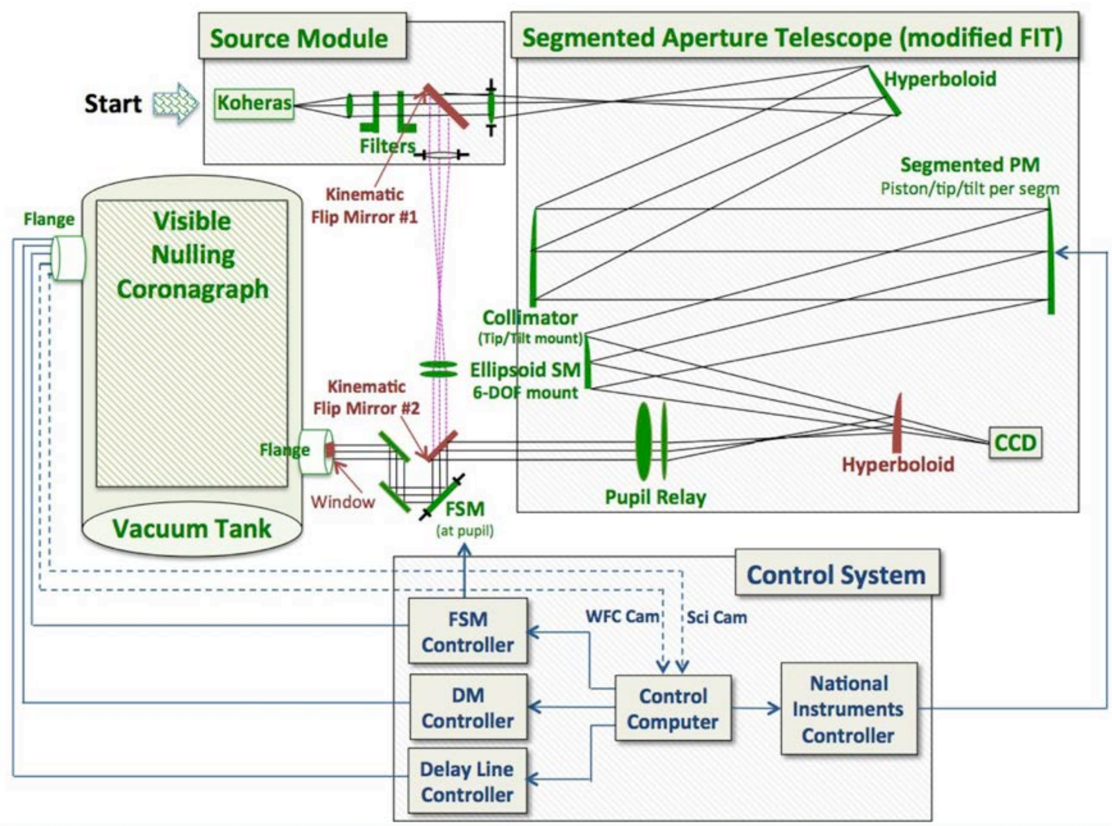

Figure-6: *Segment Aperture Interferometric Nulling Testbed (SAINT)*. Testbed will consist of 4 primary subsystems: (i) Source Module, (ii) Segmented Aperture Telescope, (iii) Visible Nulling Coronagraph, and (iv) the Control System. SAINT will demonstrate high-contrast imaging through a segmented telescope, develop coupled sensing & control, and assess closed-loop contrast and inner working angle over a finite spectral bandpass of $\Delta\lambda$ = 20 nm centered on 633 nm.

containing the VNC resting on top of the table. The control system consists of the control computer, electronics, device drivers and controllers, operating in a real time operating system (RTOS) version of Linux running C with message passing interface (MPI) for threading across 12 hyper-threaded processors. The control system is on a separate table such that stress relieved, and vibration isolated, cables are connected from it to the floating air table. Underneath feet of the vacuum tank as passive isolators and the VNC in tank rests on a shelf on a 3-point mount with each mount point passively isolated.

The proposed laboratory work is discussed in Section 2.2, the technologies in Section 2.3 and following, with a plan to achieve the milestones for this proposal is outlined in Section 2.5. The science enabled by maturing the VNC is fully attuned to NASA's strategic goals and research objectives, and those outlined by the EXOPTF. The recent image detection of exoplanets around stars, for examples see Fomalhaut by HST (Kalas et al. 2008) and HR8799 (Marois et al. 2008), have provided impetus to proceed to a mission dedicated to the space-based imaging of exoplanets.

Technical approaches to high contrast imaging are based either on Lyot coronagraphs, or interferometers. The metric usually employed to assess such techniques is the contrast at a given inner working angle. Our science team believes that these approaches also have to be assessed from the perspective of their impact on systems-level performance. Maturing a specific coronagraphic technique to TRL-6 is of little value if it drives scientific payload or spacecraft requirements such as alignment, thermal stability and pointing jitter into the regime of low TRLs. Coronagraphic technology for exoplanets has advanced significantly in the past 10 years and the leading approaches are capable, in theory, of achieving the required contrast, now the critical differences between them relate to systems-level impact, and the fraction of time spent pointed to a target star dedicated to science, i.e. observing efficiency.

For this reason, our team conducted a trade study of techniques suitable for an Exoplanet Probe Class Mission, and selected the Visible Nulling Coronagraph (VNC). The primary goal of this effort will be to further advance and step towards maturing the VNC with segmented aperture; it further advances the TRL with regards to broadband contrast and broadband sensing and control. The current VNC is at TRL-4 but all the subsystem technologies, except for the DM are at TRL-5. The ongoing TDEMs will advance the DM to TRL-5, and after completion of this proposed effort the TRL for sensing and control will TRL-6. TRL-6 is defined by "System/subsystem prototype demo in a relevant end-to-end environment" while the environment is not vacuum for the entire testbed the sensing and control algorithms it is however a 'relevant environment' since the argument that algorithms working in air would work

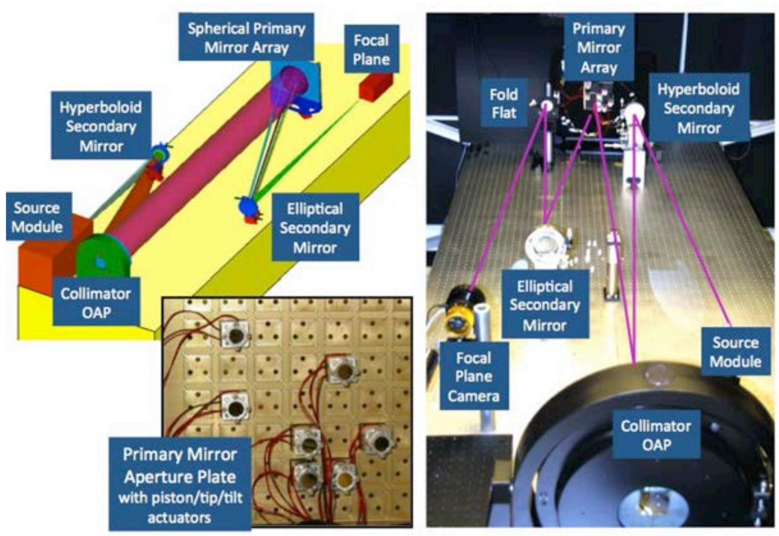

Figure-7: *SAINTs Segment Aperture Telescope.*

better in vacuum. However, this is not the case for the hardware and we do not claim TRL-6 for it.

2.3 Segmented Aperture Telescope

The segmented aperture telescope is based on two modifications to Fizeau Interferometry Testbed (FIT) (Figure-7). FIT was originally used to study wavefront control (Lyon 2004) with formation flying for the Stellar Imager (SI) Mission (Carpenter 2005). Figure-7 upper left shows a CAD model of FIT and upper right an annotated photograph. Light enters from the source module, as it does in SAINT, and reflects off a hyperboloid secondary mirror to a reflecting off-axis parabolic collimator and reflects off the segments on the aperture plate. The bottom middle of Figure-7 is a photograph of the uncovered aperture plate – nominally the regions between the segments are covered with absorbing material to mitigate stray light. The segments on the plate are flexure mounted on piston, tip, and tilt piezo based rigid body actuators. Each segment is a section of a sphere with the same radius of curvature. The displayed aperture pattern is for a non-redundant pattern (Golomb array) on a segment-to-segment grid (pitch) of 1-inch. The PM is the aperture stop and entrance pupil of SAINT. After the PM light reflects off an elliptical secondary and into the focal plane camera. The two conic secondary mirrors are designed to aberration correct the spherical aberration of the spherical segments and results in a spherical and coma free image. Residual astigmatism is small due to the limited FOV.

The two modifications are: (i) replacement of the circular segments with hexagonal segments and such that the gap between the segments is small relative to the segment size, and (ii) insertion of a pupil relay consisting of a small (1-inch) hyperboloid reflector just prior to focusing onto the camera followed by an adjustable macro zoom lens. The hyperboloid is shown in SAINT (Figure-6) at the bottom center of the box labeled 'Segment Aperture Telescope'. The pupil relay, relays the entrance pupil to a pupil on the FSM that corrects jitter induced pointing errors between the telescope and VNC. Source module light can be selected to directly enter the VNC without passing through the telescope by picking up Kinematic Flip Mirror #2 and placing it as Kinematic Flip Mirror #1. This enables alignment and control using just the VNC. Kinematic since it is 3-point mount based on 3 small spheres into which grooves on the bottom of mirror mount are set. Alternatively removing flip mirror #1 and the last hyperboloid allows alignment of the telescope via image based wavefront control from CCD images. Thus the telescope and VNC can be independently aligned and operate prior to operating the end-to-end system and for debugging purposes.

All the optics and mounts and segment actuators for the segmented aperture telescope have been procured and are assembled under the FIT project (APRA funded) and are already available to this effort at no cost except for the hyperboloid just prior to the CCD, its mount, and the hexagonal shaped spherical segments - this will be procured within this effort. We have an initial vendor quote for the segments of $4,500 with protected aluminum coatings and made of high-grade fused silica – the quote will need to be adjusted pending design completion pending the selection of this proposed effort. The low hardware costs represent significant leveraging to the SAINT proposed effort, in that no cost is incurred for the existing components, and they have already been mounted and aligned. This lowers overall risk to the effort since most of the telescope is complete. Additionally the IRAD and TDEM developed VNC is low risk since it is operational.

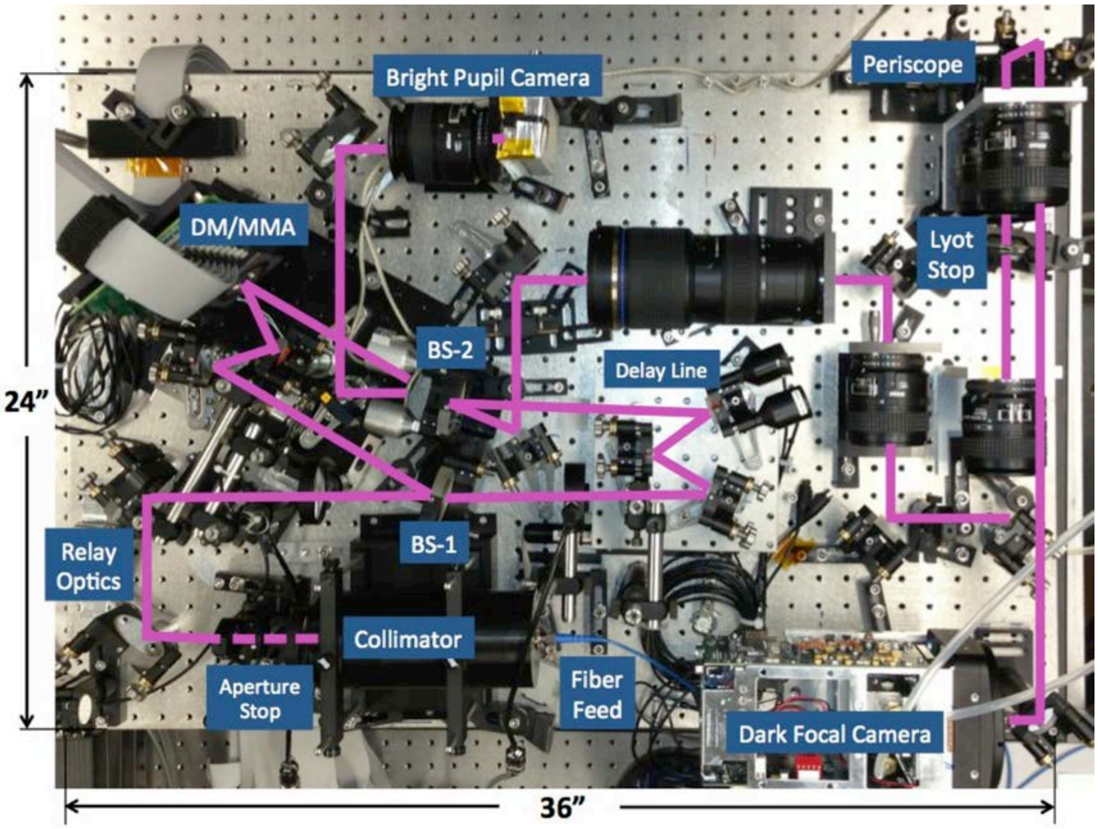

Figure-8: *Annotated Photograph of Lab VNC* showing major components

2.4 Visible Nulling Coronagraph

The ***VNC is a hybrid coronagraph that employs a combination of active and passive components to achieve the desired contrast at small IWA and over a finite spectral bandpass***. In its most simplistic form it works by destructive/constructive interference, such that placing a star on a null (destructive interference) moves the star light from the science channel to the *bright pupil ca*mera (Figure-8) for wavefront and fine pointing control, and placing the planet on a constructive interference maxima allows transmission of the planet light to the *dark focal camera* for science. An operational concept for the VNC is detailed in Clampin (2011). Our team selected the VNC for high contrast imaging due to performance trades that offer key benefits in terms of scientific productivity, and feasibility of implementation in a Probe-class or larger flagship mission. Table-1 summarizes the key benefits of the VNC that make it an excellent choice for a space-based coronagraph and an important technology to mature to TRL-6 for future exoplanet missions.

The ability to work at 2 λ/D is especially important to maximize the discovery space for exoplanets, for a given telescope aperture. However, it is notable that even within 2 λ/D the VNC delivers a lower but useful contrast to ~1 λ/D.

Initially the VNC appears complex (Figures-8&9), until one recognizes that all the critical optics between beamsplitters-1 (BS-1) and beamsplitters-2 (BS-2) are flat, including the beamsplitters, except for the DM, aka multiple mirror array (MMA). The optics prior to BS-1 would need to

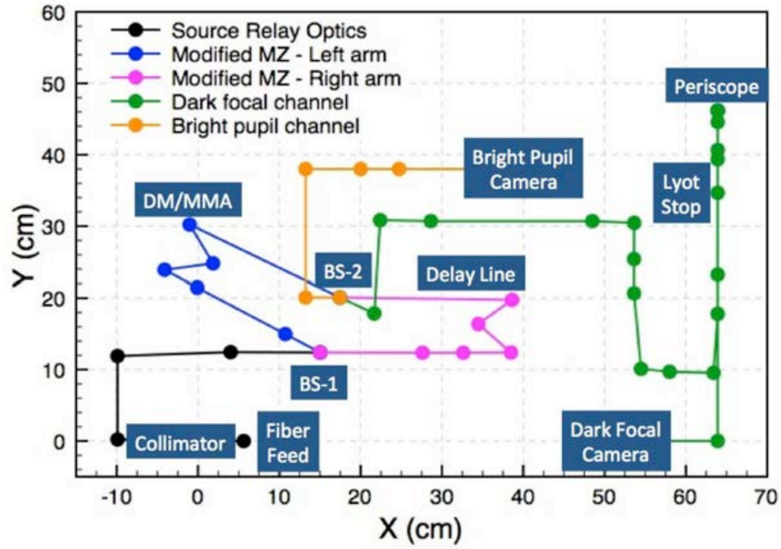

Figure-9: *Simplified VNC layout with major components*.

exist for any coronagraph to re-image the telescopes entrance pupil onto the DM and to supply light to the coronagraph. The dark focal camera optics after BS-2 would also be required for any coronagraph to image the pupil onto the Lyot stop and subsequently bring it to focus. The bright pupil channel is the same as in any coronagraph that has active wavefront control and is analogous to the picking light off the front of an occulting mask. Thus the actual nulling coronagraph contains 8 non-common path optics (5 coated flats + 2 beamsplitters + 1 DM), all of which are flat except for the DM. There is a delay line used at the outset of an observation to set the location of the broadband fringe and to perform low order wavefront sensing to flatten the DM; all fine control is done with DM. The annotated elements shown on Figure-8 are also shown on Figure-9 in a simplified format with a distance scale. The laboratory testbed includes beam chopping optics and polarizers that are in the process of being removed for SAINT and are not needed for flight. The beam choppers were only used during the previous TDEM to assess the PSF w/o nulling by shutting one shutter collecting images and opening that shutter and closing the other. The average of the two represents the un-nulled starlight needed to estimate contrast. However, with the star and planet emulator, we measure true contrast in-situ. The polarizers were only a temporary solution until the APS is complete.

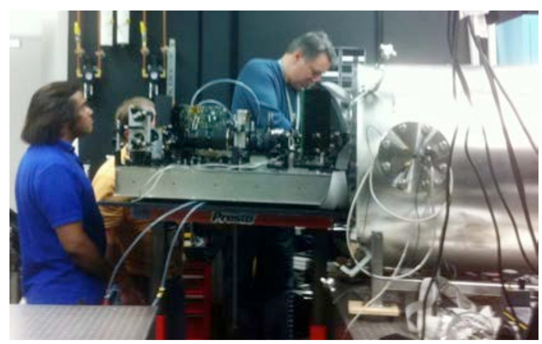

Figure-10: VNC being inserted into into Vacuum Tank by team members U. Mallik (left) and P. Petrone (right)

Vacuum feedthroughs pass through tank bulkheads, one on either side, and consist of optical fiber, electrical, and water chiller feedthroughs for camera cooling. Additionally a master heat strap resides to flow heat from the hot chips on the camera to walls of the tank.

The VNC provides, via its interferometer signal, all of the outputs required to track pointing jitter, to move and control the FSM, and to sense and control the segment level wavefront error, and the residual non-common path error (via the DM). Perhaps the most important advantage of the VNC ***is that it can null to high contrast using the starlight from the centrally nulled star and the residual speckle in the science image***. The VNC wavefront is sensed by using both its output channels and it is independent of how dark the science channel is, since as the dark science channel becomes successively darker on each control step the bright channel becomes successively brighter due to conservation of energy. WFC control is independent of how the photons are distributed between the output channels and only driven by the aggregate sum of the two. From a systems point of view one trades the stellar photon rate, against the useful fraction of science time, against the system stability requirements. The VNC optimally uses all the photons available, and levies the least restrictive stability requirements while allowing science observations of close to 100% of the time while pointed to the target star.

The VNC converges rapidly since it uses the rejected stellar photons. This capability will prove to be an important consideration in terms of the cost and feasibility of designing a probe class mission and for future flagship.

The final benefit afforded by the VNC is its scalability, both to larger aperture telescopes (e.g. ATLAST; Postman et al. 2008), and to large baseline, dilute-aperture telescopes such as DaVinci (Shao et al. 2008). Thus, our past technical demonstration of the VNC, and this proposed effort provide the technical foundation to scale to larger apertures. Our team has gained valuable experience and insight in its ongoing efforts to mature the VNC technology and the addition of a segmented aperture telescope gives NASA a trade space that includes segments and on-axis

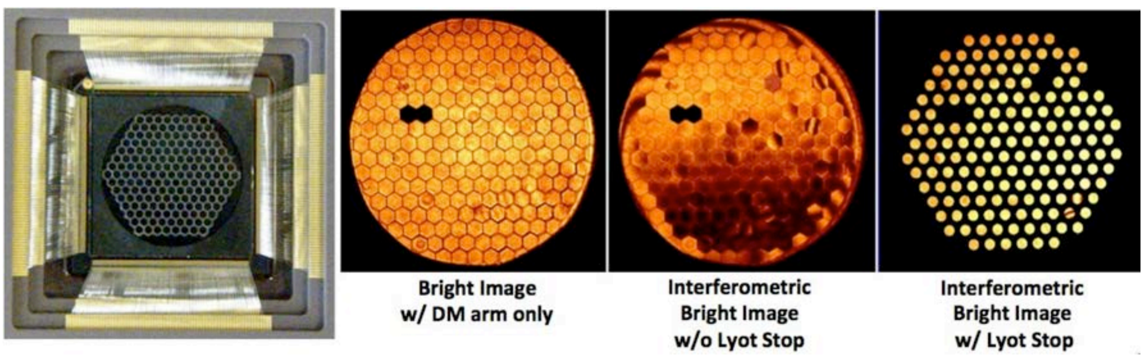

Figure-11: Photo of DM/MMA (far left) and observed images of it on the bright pupil camera. (2nd from left) one arm of VNC blocked, (2nd from right) both arms open creating interference fringes, and (far right) both arms open and imaged through Lyot stop.

obscured telescopes.

2.6 Technologies

Deformable Mirror / Multiple Mirror Array: The MMA is a hexagonal packed segmented MEMS deformable mirror developed under a phase-II SBIR with IRIS-AO and consists of 169 segments (Figure-11) of which 163 segments are actuated, the 6 outermost segments are not controlled and reside outside the beam footprint. Each segment is actuated in the 3-DOF of piston, tip and tilt and can move over the range of 0 to 1 micron in piston, and ~200 arcseconds in tip and tilt. The MMA was delivered to GSFC in May of 2010 and integrated into the VNC and is operational on a daily basis. Each of the MMA segments is 606.22 microns flat-to-flat with gaps of 4 – 5 microns and each segment is ~2 - 4 nm rms surface error and segments are made of single crystal silicon coated with protected aluminum. The full width (from left to right) of the longest row of segments is 9.2 mm. The operating MMA has already been employed to achieve our recent milestone and will be used to achieve our next milestone and the milestone proposed herein.

Achromatic Phase Shifter: The APS is detailed in Bolcar (2012) and it works by using two pairs of small (~1 cm) coated prisms. One prism pair per arm but clocked 90° in one arm relative to the other. The APS is a monolithic bonded all glass device that exploits the achromaticity of the phase difference between the **s** and **p** polarization states to perform achromatic and polarization insensitive nulling. The use of the APS allows broadband and high throughput nulling and represents the culmination of our ongoing TDEM. It will be employed in SAINT to demonstrate broadband dark holes with a segmented aperture telescope.

Table 2: *SAINT Requirements*

SAINT Top-Level Requirements	
All components in VNC	Vacuum compatible
Center wavelength	630 nm
Full bandpass FWHM	680 - 780 nm (Oxygen A-band line in passband)
Source	Koheras super-K w/ fiber feed and 3x overfill
Pupil Diameter at DM/MMA	1.6608 cm
Entrance Pupil	@ Telescopes aperture plate
Image pupil relay	Relays DM image to SFA in dark output
Image Plane Sampling	2.0 arcsec (λ/4D @ 630 nm)
Image Plane Detector Pixel	16 microns (EMCCD)
image Effective Focal Length	825 mm
Image F/#	99.34
Image format (EMCCD)	512 x 512
Image FOV	34 x 34 arcmin (64 x 64 λ/D)
VNC achieved contrast @ 2 lam/D	5×10^{-9} at 2 λ/D = 8 pixels in 100 nm passband
Exit pupil (bright output)	MMA image relayed to pupil imaging CCD
Pupil Plane Pixel	16 microns
Pupil format	1024 x 1024 x 16 bit CCD (256 cpa)
Pupil relay mirrors afocal mag	2x
MMA Format	IRIS-AO MEMS DM, 169 segments w/ 163 actuated, hex pack with piston/tip/tilt control per segment and 4 nm rms / segment, 16-bit electronics, 611.218 micron pitch
SFA Format	217 fibers (434 lenslets), 500 micron pitch, each fiber optically mapped to one MMA segment. Pupil relay has mag of 1.222
Null Control Approach	Closed-loop simultaneous sensing of bright/dark outputs w/ feedback to MMA and piston mechanism @ 40 Hz
Input WFE (static)	< 63 nm rms WFE
Input WFE (dynamic)	< 5 nm rms WFE (1-σ) stability
Controlled WFE stability	~70 picometers rms with MMA & SFA
Controlled RMS Reflect Error	0.05 % with MMA & SFA
Differential Polarization	0.01 degrees

2.7 Modeling and Analysis of SAINT

Modeling and analysis plays a large role in setting the requirements, modeling the sensitivities and understanding the behavior of the SAINT. We have previously developed a beam propagation model of the VNC and have used this for error budgeting on the EPIC ASMC study and for setting requirements and error budgeting the existing VNC testbed. Some of this analysis has also been done during the design phase of FIT. We will couple the two models together as a component of this effort and update the telescope model to include the hexagonal segments and their control parameters. Then we will develop a sensitivity analysis to as a set of parametric functions as a function of what we believe to be the major drivers for this effort. The set of parametric functions will be incorporated into a spreadsheet model to develop and assess end-to-end errors budgets. The model will be successively refined throughout this effort based on lessons learned and the measured data sets.

All the technologies are well in hand to realize SAINT – we have contributed to all of them and worked with the vendors and university groups to advance the critical technologies; now is the time to put them together to realize an end-to-end systems demonstration of the telescope plus coronagraph architecture. The proposed effort is timely since the end date 2015 coincides with beginning of the technology down select for an exoplanet probe class mission or as an instrument on the Wide-Field Infrared Survey Telescope (WFIRST) mission planned for early next decade.

3. Impact

Maturation of the VNC for segmented apertures has near- and long-term impacts on the state of knowledge for coronagraphy and systems architecture for exoplanets. In the near term demonstrating broadband high contrast imaging with a segmented aperture is a key milestone to achieving TRL-6, for end-to-end performance of the VNC, and enables consideration of the VNC technology for future filled or segmented aperture missions. This is important for NASA as it provides the flexibility to trade several competing architectures and technologies and select the approach that yields the best science return balanced against costs and risk. In the longer term, the VNC may be the most appropriate high contrast technology for large flagship missions with segmented mirrors and would enable NASA to address goal in detecting and characterizing terrestrial planets in the search for life on other worlds. Also, WFC algorithms we have developed have benefit across all high contrast techniques.

4. Relevance to the Program Element

The proposed effort addresses NASA Strategic Goal 3.D to "*Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets*" by addressing technologies ultimately needed to search for Earth-like planets to help answer the question of "*Are we alone?*". Technology for direct imaging of exosolar planets also addresses the NASA Science Plan research objective to "*create a census of extrasolar planets and measure their properties*." Critical to realizing reasonably priced exoplanet imaging missions is the VNC and this effort advances technology readiness levels of critical technology in the TDEM areas of:

Broadband Starlight Suppression Demonstration: SAINT enables rejection of diffracted and scattered starlight so that light from an exoplanet can be separated from its parent star in broadband.

Broadband Wavefront Sensing and Control: Broadband closed-loop control, with MMA, achromatic coatings, and broadband WFC achieves starlight rejection through segmented aperture, by controlling the differential light paths within the VNC. This advances sensing and control.

***Advanced Optics**:* Use of the SFA reduces number of control degrees of freedom, allowing control of wavefront and amplitude errors with a single DM. It advances broadband understanding of SFA.

***Segmented Aperture System Performance Assessment**:* The proposed effort will take a large step towards validating nulling and control models for segmented apertures in broadband, and further validate the model of the coupled segmented aperture telescope with the VNC.

5. Plan of Work

Our team has defined a focused activity with clearly defined goals leading to a milestone (Table-3). The PI is responsible for the success of this program and will be involved in every aspect of the design, implementation and execution of the experiments. We are requesting salary support for personnel and for the procurement of the components associated with integrating the VNC to the segmented aperture telescope. A detailed summary of personnel, roles and responsibilities is presented in the budget narrative.

5.1 Key Milestones

The key milestones are: (i) installation of hex segments, (ii) integration of existing VNC with segmented aperture telescope to complete SAINT, (iii) installation of FSM, (iv) coupling and optimization of real time control system from the VNC with telescope segment control and FSM, (v) and the end-to-end high contrast broadband imaging. Tasks 1 and 5 are the initial and final TAC reviews respectively; all team members will contribute. Most of the effort is concentrated within tasks 2, 3 and 4. Task 2 is a lab hardware effort to integrate SAINT and bring it to full operations and uses primarily P. Petrone, T. Madison, R. Lyon and M. Bolcar, and relies on Task 3 completing on time at the beginning of 4th quarter of year-1 to enable device control. Task-3, led by B. Hicks with a contributing software engineer, consists of assembling the software, device drivers, and bring the control system to full operations. Task-4 is led by R. Lyon (for the VNC) and K. Carpenter (for the FIT segmented aperture telescope), and draws upon needed support from the GSFC Optics Branch. K. Carpenter will provide additional oversight on the integration of the telescope with VNC to form SAINT. M. Clampin will lead the performance evaluation, assessment of the milestone achievement and contribute to assembling of, and review of, the initial and final whitepapers.

The effort represents an easily manageable effort in a 2-year time with the critical path at the junction of tasks 2.7 and 3.5. The small team is in residence at GSFC (all in Building 34) as is all the hardware. This negates travel costs and time other than to present results. Proximity of team to each other and hardware creates a dynamic, fast paced interactive goal oriented environment that enables completion of complex systems with daily informal meetings.

Year 1:

- Assemble initial milestone whitepaper and present to the TAC.
- Procure and mount spherical hexagonal telescope PM segments.
- Procure and install the glass window in the existing vacuum tanks flange.
- Integrate FSM and control code from VNC, FIT. Demo control of each device.

Year 2:

- Complete integration of VNC w/ telescope; bring to full operational readiness.
- Fine tune and implement changes to wavefront control (task 4.3)
- Assess broadband contrast performance as function of IWA
- Complete final whitepaper and present to the TAC, and TAC review.

5.2 Leveraging

B. Hicks is a NPP post-doc, there is no charge for his time for 1st year of this effort (FY15).

6. Data Sharing Plan

All results to realize milestones will be documented and in conference proceedings and/or peer-reviewed journals. Additionally specific requests for laboratory datasets, will also given to those who request it for further analysis and evaluation. All past work on the GSFC VNC testbed has been openly reported at AAS meetings and published in SPIE proceedings.

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Glossary of Acronyms

ASMC	Astrophysics Strategic Mission Concepts
ATLAST	Advanced Technology Large-Aperture Space Telescope
APS	Achromatic Phase Shifter
COTS	Commercial off the shelf
DAViNCI	Dilute Aperture Visible Nulling Coronagraph Imager
DM	Deformable Mirror
EPIC	Extrasolar Planetary Imaging Coronagraph
FIT	Fizeau Interferometry Testbed
FSM	Fast Steering Mirror
GSFC	Goddard Space Flight Center
HZ	Habitable Zone (range of planet orbits where liquid water could exist)
IWA	Inner Working Angle
IRAD	Internal Research and Development
MEMS	Micro Electrical Mechanical Structure
MMA	Multiple Mirror Array, aka hex-packed segmented MEMS deformable mirror
MPI	Message Passing Interface, software paradigm for parallel programing
MZ	Mach-Zehnder interferometer
PM	Primary Mirror
OTE	Optical Telescope Element
PSF	Point Spread Function (image of an unresolved star)
RTOS	Real Time Operating System
SAINT	Segmented Aperture Interferometric Nulling Testbed
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovation Research
SFA	Spatial Filter Array
SI	Stellar Imager
SM	Secondary Mirror
SVIP	Solar Viewing Interferometry Prototype
TAC	Technical Advisory Committee, Exoplanet committee to evaluate technology
TDEM	Technology Development for Exoplanet Missions
TM	Tertiary Mirror
TRL	Technology Readiness Level
VNC	Visible Nulling Coronagraph
WFS	Wavefront Sensing
WFC	Wavefront Control

Biographical Sketches

Richard G. Lyon

Exoplanets and Stellar Astrophysics Laboratory — Principal- Investigator

Current Position

Optical Scientist - NASA/Goddard Space Flight Center (Code 667)

Research Areas

Instruments for exo-solar planetary detection, imaging interferometry, complex systems modeling on parallel computers, wavefront control systems

Relevant Experience

2000 to present – Optical Scientist, NASA/Goddard Space Flight Center
1994 to 2000 – Research Scientist, GSFC CESDIS, through the University of Maryland
1992 to 1994 – Optical Researcher, Air Force Research Labs, Geophysical Directorate
1987 to 1992 – Optical Systems Engineer, Perkin-Elmer (Later Hughes Danbury Optical)

Education

B.S. Physics (Magna Cum Laude), 1985, University of Massachusetts
M.S. Optics, 1987, University of Rochester, Institute of Optics
Studies toward Ph.D, Optics, 1987, University of Rochester, Institute of Optics

Professional History

R. Lyon joined NASA/GSFC in 1994 as Scientist for the Center of Excellence in Space Data & Information Systems and has been involved in the Hubble Space Telescope and wavefront control for James Webb Space Telescope. He is a member of the Exoplanets and Stellar Astrophysics Lab at NASA/GSFC and has led efforts in modeling & algorithm development, imaging inteferometry and visible nulling coronagraphy and is Project Scientist for the Extra-Solar Planetary Imaging Coronagraph (EPIC). Previously at AFRL, he was involved in the Mid-Course Space Experiment and at Perkin-Elmer he was PI for the Hubble Space Telescope phase retrieval efforts to quantify the telescope errors.

Honors and Awards

- NASA James Kerley Award, for Wavefront Sensing (2012)
- NASA Medal for Exceptional Service, August 2004.
- NASA Special Act Awards, 2005, 2004, 2002, 2001.
- NASA Group Awards for Horizon (2001), JWST WFC (2001), AGS (1999).
- NASA/GSFC Certificate for "Contributions to the Hubble Space Telescope, 1991.
- NASA Group Achievement Award for HST Mission Operations Team, GSFC, 1991.
- Award for "Hubble Space Telescope Phase Retrieval", Hughes Danbury Optical, 1991.
- Award for Hubble Space Telescope Launch and Orbital Verification", HDOS, 1990.
- Departmental Prize, University of Massachusetts for honors in Physics, 1985.

Recent Relevant Publications

Authored or co-authored ~150 publications in Astronomy, Optics and Applied Mathematics.

[1] Lyon, R.G., Clampin, M.C., Melnick, G.J., Tolls, V., Woodruff, R.A., Vasudevan, G., Rizzo, M., Thompson, P.L., *Visible Nulling Coronagraph Testbed Results*, Proc of SPIE 7440 (2009)

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Dr Mark Clampin: NASA's Goddard Space Flight Center Co-Investigator

Current Position

2003 to Present: JWST Observatory Project Scientist, NASA/GSFC, Code 667 Research Areas: Formation of planetary systems, astronomical instrumentation

Education

1986 – Ph.D. Physics, University of Saint Andrews
1982 – B.S. Physics, University of London

Relevant Experience

2000 to 2003: Scientist, STScI (ACS Instrument Group Manager), STScI
1996 to 2000: Associate Scientist, (ACS Instrument Group Manager), STScI
1992 to 1996: Assistant Scientist, WFPC2/STIS Instrument Scientist), STScI
1988 to 1992: Associate Scientist, (STIS Optics Scientist), JHU
1986 to 1988: European Space Agency Fellow, STScI

Professional History

Dr. Clampin is currently the James Webb Space Telescope (JWST) Observatory Project Scientist at GSFC, a position he assumed in 2003 when he joined GFSC. Dr. Clampin is the Principal Investigator of the Exosolar Planetary Imaging Coronagraph (EPIC), a Discovery Class mission concept employing a visible nulling corongraph. Dr. Clampin is the Principal Investigator of a TDEM study to mature VNC technology. Dr. Clampin is a Co-Investigator on the Advanced Camera for Surveys (ACS) science where he served as the Detector Scientist. Previously, Dr. Clampin was a Scientist at STScI, where he gained ten years experience in HST instrument commissioning and science operations at STScI. He served as manager of the ACS Instrument Group at STScI from inception through the SM3B servicing mission orbital verification. Dr. Clampin is a member of the team that discovered and imaged the exoplanet Fomalhaut-B.

Recent Honors and Awards

2010: NASA Science Medal
2010: AAAS Newcomb-Cleveland Prize
2003 Servicing Mission 3B Flight Team Award
1999 National Resource Award for Science Leadership on HST SM 2
1995 STScI achievement award

Selected Publications

Clampin, M. Smith, E 2010, "Overview of the JWST" SPIE 7731, 107.
Kalas, Paul; Graham, James R.; Chiang, Eugene; Fitzgerald, Michael P.; Clampin, Mark; Kite, Edwin S.; Stapelfeldt, Karl; Marois, Christian; Krist, John 2008, "Optical Images of an Exosolar Planet 25 Light-Years from Earth", Science 322 5906.
Clampin, M. and Smith, E. 2010, "Overview of the James Webb Space Telescope Observatory" SPIE 7731, 07
Clampin, Mark et al. 2006, "Extrasolar planetary imaging coronagraph (EPIC)", SPIE, 6265

Dr. Kenneth G. Carpenter (Collaborator)
Current Position: Astrophysicist and Operations Project Scientist for Hubble Space Telescope - Laboratory for Astronomy and Solar Physics, NASA/GSFC.
Education:

B.A. (Astronomy) Wesleyan University - 1976 *cum laude*

M.A. (Astronomy) Wesleyan university - 1977

Ph.D. (Astronomy) Ohio State University - 1983

Research Interests: Ultraviolet Spectroscopy. Chromospheres, transition regions and winds of cool stars. Stellar Activity. Model atmospheres and synthetic spectra. Fluorescent processes. Instrument development. Interferometric systems. PI of Stellar Imager Vision Mission Study.

Publications: 70 Refereed papers, 93 Other Major Publications and Review Talks, and 80 abstracts of meeting presentations. Publications include:

- Carpenter, K.G., Robinson, R.D. Wahlgren, G.W., Ake, T.R., Ebbets, D.C., Linsky, J.L., Brown, A and Walter, F.M. 1991,"First Results from the GHRS: The Chromosphere of Alpha Tau", ApJ (Letters), 377, L45.
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Peter Petrone - CO- INVESTIGATOR
Sr. Optical Engineer
Sigma Space Inc.,
Goddard Space Flight Center, Greenbelt, MD.

2003-Present
Current Position:
Sr. Optical Engineer - Sigma Space Incorporated / NASA Goddard Space Center Code 551

Relevant Experience:

2003-Present Sr. Optical Engineer Sigma Space Inc., GSFC
1998-2003 Optical Engineer IV Management Technologies Incorporated, GSFC
1996-1998 Optical Engineer III Management Technologies Incorporated, GSFC
1989-1996 Optical Engineer Hughes Danbury Optical Systems Inc., Danbury

Education:

Master of Science, Physics, Concentration Optics, Fairleigh Dickinson University, NJ. 1989
Bachelor of Science, Physics, Fairleigh Dickinson University, NJ. 1988

Professional History:

P. Petrone has provided support to a range of flight and research activities at NASA/GSFC since 1996. He is currently involved in the development and testing of optical hardware used to validate and refine methodologies for advancing the science of high contrast nulling interferometry. Prior to this work, he was involved in the development and use of numerous metrology stations that characterized the HST Advanced Camera for Surveys (ACS) filter set. Mr. Petrone was involved in the fabrication, alignment and research activities associated with the James Web Space Telescope Wavefront Sensing and Control Testbed at GSFC. This testbed (utilized by GSFC and JPL) was instrumental in the early development of control algorithms proposed for the coarse alignment and fine phasing of the JWST primary mirror segments.

Recent Projects

<u>HST Independent Verification and Test (IVT)</u>
Supported the Independent Verification and Test Team (IVT) engaged in verification testing of the HST Wide Field Camera 3 (WFC3). Participated in the calibration of the HST optical stimulus CASTLE and its use in the ambient and vacuum testing of WFC3.

<u>Visible Nulling Coronograph (VNC)</u>
Worked with GSFC and Lockheed Martin personnel to assemble, align and characterize the optical performance of the VNC nuller. Acquired the initial null and improved VNC performance by addressing environmental and opto-mechanical concerns that compromised fringe contrast. Achieved a null using two achromatic phase plates and investigated their potential for enhancing the null depth of the instrument.

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PROFESSIONAL EXPERIENCE:

NASA Goddard Space Flight Center, Greenbelt, MD
Research Physicist (Jan. 2009 – present) – Optics Branch, Wavefront Sensing & Control Group
3M Corporation, West Haven, CT
Engineering Co-op (June 2001 – Sept. 2001) – Specialty Fiber Optics Division
3M Corporation, St. Paul, MN
Engineering Co-op (Sept. 2000 – Dec. 2000) – Fiber Optic and Electronic Materials Technology Center

EDUCATION:

University of Rochester, Rochester, NY
Ph.D., Optics, March 2009
Advisor: Dr. James R. Fienup
Dissertation: Phase Diversity for Segmented and Multi-aperture Systems
Cornell University, Ithaca, NY
B.S., Engineering Physics, May 2002

RECENT PROJECTS:

Advanced Technology Large Aperture Space Telescope (ATLAST) – Optical Systems Engineer; Technology Roadmap Team member (2013-present)
ICESat-2 Advanced Topographical Laser Altimeter System (ATLAS) – Receiver Telescope Assembly Wavefront Sensing Lead (2013-present)
LandSat-8 Thermal Infrared Sensor (TIRS) – Wavefront sensing test of telescope (2009-2011)

HONORS & AWARDS:

Robert H. Goddard Award – Outreach – 2013, NASA GSFC
NASA Group Achievement Award – 2013, Wavefront Sensing and Control Group
NASA Group Achievement Award – 2013, TIRS Instrument Development Team
Robert H. Goddard Award – Exceptional Achievement for Engineering – Team – 2013, TIRS Instrument Development Team
Instrument Systems & Technology Division New Achiever Medal – 2010, NASA GSFC
Frontiers in Optics Outstanding Student Paper – 2008, Optical Society of America for "A Comparison of Regularized Metrics for Phase Diversity"
Graduate Student Research Program Fellow – 2005-2008, NASA Goddard Space Flight Center
Student Optical Design Competition – 2005, Optical Research Associates for *Design of a Sparse Aperture Interferometric Telescope*
Chapter Service Key & Certificate of Recognition for the Brother Most Exemplifying Leadership – 2001, Phi Sigma Pi National Honor Fraternity, Beta Nu Chapter

PROFESSIONAL SOCIETIES & LEADERSHIP POSITIONS:

Optical Society of America – member since 2004
SPIE – member since 2005
American Association for the Advancement of Science – 2009 - 2013
North American Tae Kwon Do, Rochester, NY – 2nd Dan, Assistant Instructor 2007-2008
Junior Graduate Representative – The Institute of Optics, Fall 2003 – Spring 2004
Phi Sigma Pi National Honor Fraternity – Brother since 1999, Vice President of Beta Nu Chapter 2001, Scholarship Chair of Capital Alumni Chapter 2013-present

Dr. Brian Hicks: NASA Goddard Space Flight Center

Current Position

January 2014 to Present: NASA Postdoctoral Program Fellow – Code 667
Research Areas: Astronomical instrumentation, exoplanetary systems

Education

2012 – Ph.D. Electrical Engineering, Boston University
2006 – M.A. Astronomy, Boston University
2002 – B.A. Physics, Macalester College

Relevant Experience

2012 to 2013: Postdoc Research Fellow, Center for Atmospheric Research, UMass Lowell
2004 to 2011: Research Assistant, Center for Space Physics, Boston University

Professional History

Dr. Hicks recently joined the Exoplanetary and Stellar Astrophysics Laboratory at NASA GSFC to help the Visible Nulling Coronagraph (VNC) reach its next technology demonstration milestone of broadband 10^9 suppression. Prior to this, he was a Postdoctoral Research Fellow at the UMass Lowell Center for Atmospheric Research where he was one of the leads building the Space Physics Laboratory featuring a stable space-like environmental chamber and infrastructure for building and testing sounding rockets. During this time, Dr. Hicks was the optics lead for the Interstellar Medium Absorption Gradient Experiment Rocket (IMAGER), designing, building, testing and integrating a multiband UV camera, as well as overseeing launch preparations at Wallops Flight Facility (WFF) and November 2012 launch from White Sands Missle Range (WSMR). As a graduate student at the Boston University Center for Space Physics, Dr. Hicks led the telescope alignment and instrument integration for the Planetary Imaging Concept Testbed Using a Rocket Experiment (PICTURE), for which he traveled to WFF to perform final flight readying, integration with payload support systems, and environmental testing, as well as WSMR to perform launch pad preparations and in-flight command uplink in October 2011.

Recent Honors and Awards

2013: NASA Postdoctoral Program Fellowship
2009: NASA International Year of Astronomy Student Ambassador

Selected Publications

Hicks, B., Chakrabarti, S., Cook, T., *Interferometric nulling limits with tip-tilt-piston deformable mirrors and a pinhole spatial filter array*, J. Astron. Tel. Inst. & Sys., In production (2014).

Hicks, B., *Nulling interferometers for space-based high-contrast visible imaging and measurement of exoplanetary environments*, Springer, New York, (2013).

Hicks, B., Danowski, M., Martel, J., Cook, T., "High etendue UV camera for simultaneous four color imaging on a single detector," Appl. Opt. **52**, 5194-5200 (2013).

Mendillo, C., **Hicks, B.**, Cook, T., Bifano, T., Content, D., Lane, B., Levine, B. M., Rabin, D., Rao, S., Samuele, R., Schmidtlin, E., Shao, M., Wallace, J., K., Chakrabarti, S., *PICTURE: a sounding rocket experiment for direct imaging of an extrasolar planetary environment*, Proc. SPIE **8442**, (2012).

Hicks, B., T. Cook, B. Lane, and S. Chakrabarti, *OPD measurement and dispersion reduction in a monolithic interferometer*, Opt. Ex. **18**, 17542-17547 (2010).

Hicks, B. T. Cook, B. Lane, and S. Chakrabarti, *Monolithic achromatic nulling interference coronagraph: design and performance*, Appl. Opt. **48**, 4963-4977 (2009).

Current and Pending Support for ***Richard Lyon, PI***

Current Support:

Title: “Compact Achromatic Visible Nulling Coronagraph Technology Maturation”
Project: NASA SAT/TDEM
PI: R. Lyon
Program: NNH10ZDA001N-SAT
Total Budget: $303,712 FY12, $206,733
PI R. Lyon Commitment: 0.5 FTE in each of FY 12/13

Title: “Environmental Testing of MEMS Deformable Mirrors for Exoplanet Detection”
Project: NASA SAT/TDEM
PI: Helmbrecht
Program: NNH10ZDA001N-SAT
Total Budget: $397,664 FY12, $368,397
Co-I R. Lyon Commitment: 0.1 FTE in each of FY 13/14

Pending Support:

Title: "Segmented Aperture Nulling Coronagraphy"
PI: Richard G. Lyon (NASA/GSFC)
NASA ROSES SAT
Average Commitment: FY15: 0.40 FTE, FY16: 0.40 FTE

Title: "Wide-field Spatio-Spectral Interferometry: A Keystone Technology for NASA's Astrophysics Roadmap"
PI: David Leisawitz (NASA/GFSC)
NASA ROSES APRA
Average Commitment: FY15: 0.20 FTE, FY16: 0.20 FTE, FY17: 0.15 FTE

Current and Pending Support for Dr. ***Mark Clampin, Co-Investigator***

Current Support:

Title: “HST Astrometric search for young planets”
Project: HST
PI: Wisnieski
Program: HST/12316
Total Budget: $0.00
Co-I M. Clampin Commitment: 0.083 FTE in FY 09 through FY13

Title: “Compact Achromatic Visible Nulling Coronagraph Technology Maturation”
Project: NASA SAT/TDEM
PI: Lyon
Program: NNH10ZDA001N-SAT

Total Budget: $303,712 FY12, $206,733
Co-I M. Clampin Commitment: 0.05 FTE in each of FY 12/13

Pending Support: None

Current and Pending Support for Dr. Kenneth G. Carpenter, Collaborator

Current Support:

Title: “Advanced Spectral Library (ASTRAL) Project: Cool Stars”
PI: T. Ayres
Program: HST Cycle 18 GO
Total Budget (KGC): $ 25 K
Co-I KGC Commitment: 0.1 FTE in FY13

Pending Support:

Title: “Advanced Spectral Library (ASTRAL) Project: Hot Stars”
PI: T. Ayres
Program: HST Cycle 21 GO
Total Budget (KGC): TBD if accepted
Co-I KGC Commitment: 0.1 FTE in FY14 and FY15, if funded

Title: “Clues for Dynamo Models: Revealing Rotational Modulation of Magnetic Structures in Giant Stars”
PI: K.G. Carpenter
Program: HST Cycle 21 GO
Total Budget: TBD if accepted
Co-I KGC Commitment: 0.1 FTE in FY14 and FY15, if funded

Title: “Coordinated Ultraviolet and X-ray Variability Study of LMC X-3: Investigating Black Hole Accretion"
PI: P. Boyd
Program: HST Cycle 21 GO
Total Budget: TBD if accepted
Co-I KGC Commitment: 0.1 FTE in FY14 and FY15, if funded

Title: “Link between Circumstellar Gas and the Lambda Boo Stars”
PI: K.P. Cheng
Program: HST Cycle 21 GO
Total Budget: TBD if accepted
Co-I KGC Commitment: 0.1 FTE in FY14 and FY15, if funded

Title: “A Precision Measurement of the Mass of the Cepheid V350 Sgr"
PI: N. R. Evans
Program: HST Cycle 21 GO

Total Budget: TBD if accepted
Co-I KGC Commitment: 0.1 FTE in FY14 and FY15, if funded

Current and Pending Support for ***Peter Petrone, Co-I***

Current Support:

Title: “Compact Achromatic Visible Nulling Coronagraph Technology Maturation”
Project: NASA SAT/TDEM
PI: Lyon
Program: NNH10ZDA001N-SAT
Total Budget: $303,712 FY12, $206,733
Co-I Commitment: 0.5 FTE in each of FY 12/13

Pending Support: None

Current and Pending Support for ***Matthew Bolcar, Co-I***

Current Support: None

Pending Support:

"Segmented Aperture Nulling Coronagraphy"
PI: Richard G. Lyon (NASA/GSFC)
NASA ROSES SAT
Average Commitment: FY15: 0.20 FTE, FY16: 0.20 FTE

"Wide-field Spatio-Spectral Interferometry: A Keystone Technology for NASA's Astrophysics Roadmap"
PI: David Leisawitz (NASA/GFSC)
NASA ROSES APRA
Average Commitment: FY15: 0.15 FTE, FY16: 0.15 FTE, FY17: 0.10 FTE

Segmented Aperture Nulling Coronagraphy

GSFC PI: RICHARD LYON
Submitted in response to NNH13ZDA001N-SAT, Strategic Astrophysics Technology, D.8

Budget Justification: Narrative and Details

Notice of Restriction on Use and Disclosure of Proposal Information
The information (data) contained in this section of the proposal constitutes information that is financial and confidential or privileged. It is furnished to the Government in confidence with the understanding that it will not, without permission of the offeror, be used or disclosed other than for evaluation purposes; provided, however, that in the event a contract (or other agreement) is awarded on the basis of this proposal, the Government shall have the right to use and disclose this information (data) to the extent provided in the contract (or other agreement).

Budget Justification: Narrative

NASA Center Funding
Procurement and Travel Only

Per October 20, 2010 guidance from NASA SMD, updated April 20, 2012, for ROSES proposals, NASA civil servant labor dollars will be redacted from NSPIRES and budget justifications. Each NASA Center will separately submit its total budget that includes its civil servant labor *for subsequent retrieval by NASA Headquarters*.

http://science.nasa.gov/researchers/sara/how-to-guide/nspires-CSlabor/

NASA Center Funding By Program Year

	PY 1 Cost	PY 2 Cost	Total Cost
NASA/GSFC	193,936	199,407	393,342

Personnel and Work Efforts (by Program Year)
The following table reflects the level of support required of all personnel (including NASA civil servants) necessary to perform the proposed investigation, regardless of whether these individuals require funding from this proposal.

Name and/or Position Title	Role	Institution	PY 1 FTEs	PY 2 FTEs	Total
RICHARD LYON	PI	NASA/GSFC	0.50	0.50	1.00
MARK CLAMPIN	Co-I	NASA/GSFC	0.05	0.05	0.10
MATTHEW BOLCAR	Co-I	NASA/GSFC	0.30	0.27	0.57
PETER PETRONE, OPTICAL ENGINEER	Co-I	Sigma Space	0.50	0.50	1.00
BRIAN HICKS -NPP POST DOC	Co-I	USRA	0.00	0.33	0.33

Name and/or Position Title	Role	Institution	PY 1 FTEs	PY 2 FTEs	Total
TEST SERVICES - TECH	Support	NASA/GSFC	0.04	0.03	0.07
TEST SERVICES POOL	Support	TBD	0.04	0.03	0.07
		Total:	1.43	1.40	3.14

The proposed work level is appropriate to perform the investigation on the basis of the previous ROSES/SAT proposals and on past APRA testbed work and the experience learned therein.

GSFC Civil Servant Roles:

We are requesting salary support for personnel and for the procurement of the components associated with integrating the VNC to the segmented aperture telescope.

The PI, R. Lyon, will perform the overall lead and lead in the modeling, sensing and control and take responsibility for writing the initial and final whitepapers.

Co-I Mark Clampin will provide science oversight and will lead the performance evaluation and assessment of the milestone achievement and contribute to assembling of, and review of, the initial and final whitepapers.

Co-I Ken Carpenter will contribute to and bring oversight for the segmented aperture telescope. K. Carpenter will provide additional oversight on the integration of the telescope with VNC to form SAINT.

Co-I Brian Hicks will work with R. Lyon and Matt Bolcar on the optical layout and the sensing and control approach, and to evaluate and fine-tune the data and the results.

Co-I Matt Bolcar will work with R. Lyon and B. Hicks on the sensing and control approach for SAINT and to bring the control system to full end-to-end operations.

Co-I Peter Petrone will have overall responsibility for assembling the SAINT, mounting and aligning optics and assist in bring the system to full optical operations.

The civil servants included in this budget are proposed at the skill levels shown in the below:

GSFC Civil Servant Name	Budgeted Skill Title
RICHARD LYON	Scientist-Tier 4
MARK CLAMPIN	Scientist-Tier 4
MATTHEW BOLCAR	Engineer-Mid
TEST SERVICES - TECH	Technician-Mid

GSFC proposal budgets are based on four Scientist skill levels with Scientist-Tier 1 reflecting the experience level equivalent to GS-13-Step 6 and Scientist Tier-4 the experience level of GS-15-Step 10.

GSFC proposal budgets are based on three Engineer skill levels with Engineer-Entry representing the experience level equivalent to GS-7/9, Engineer-Mid related to GS-11/12/13, and Engineer-Senior applicable to GS-14/15.

GSFC proposal budgets are based on three Technician skill levels with Technician-Entry representing the experience level equivalent to GS-9/10, Technician-Mid related to GS-11/12, and Technician-Senior applicable to GS-13/14.

The total GSFC budget including civil servant labor dollars will be provided separately for subsequent retrieval by NASA Headquarters.

The cost of the labor (salary and fringe) is based on GSFC's established salary rates for the skill levels shown in the above table. GSFC fringe dollars are based on a percent applied to salary dollars using GSFC established rates per year.

GSFC On-Site Contractor Roles:

Co-I Peter Petrone, an on-site contractor, will have overall responsibility for assembling the SAINT, mounting and aligning optics and assist in bring the system to full optical operations. The cost estimate is based on the current cost of P. Petrone for ongoing work and for an existing contract at GSFC.

Co-I Brian Hicks is a NASA NPP postdoctoral researcher and comes at no cost to this effort for the first year. The 2nd year of this effort is actually the 3rd year of the NPP postdoc position and corresponds to the 2nd year of this effort, thus his costs would be at the rate for a 3rd year NPP postdoc.

Other Direct Costs

Materials and Supplies (ie, < $5K per unit; otherwise, see Equipment)

This table reflects GSFC's budget for materials and supplies to cover the integration of the VNC testbed to the FIT testbed and to run the high contrast experiment. Cost estimates are based on recent similar procurements and past GSFC experience with both the FIT and VNC testbeds.

Item	PY 1	PY 2	Total
7 Hexagon mirror segments	12,300	0	12,300
7 sets of flexure mounted piezo actuators	16,000	0	16,000
4" vacuum window, seals, selent material, machining	14,000	0	14,000
Adlink interface card for actuator controllers	1,800	0	1,800
Miscellaneous hardware	10,000	15,000	25,000
Total:	54,100	15,000	69,100

Travel

For each of the travel purposes below, the following standard cost assumptions:

- Estimated airfare and auto rental costs were obtained from either NASA's customary source or from other airfare estimating search engines (ie, Travelocity, etc.); also, per diem costs were obtained from http://www.gsa.gov/
- miscellaneous costs include local mileage using the current prevailing rate for privately owned vehicle (POV), obtained from http://www.gsa.gov/ , airport parking, car rental fuel, tolls, and conference fees (if applicable).
- inflation of 3% per year is applied for annual occurrences.

Cost Details

Trip 1

	Lodging	**MI&E or Per Diem**	**Airfare**	**Ground Trans**	**Auto Rental**	**Misc**	**Total**	
Rate	139	71	500	40	0	2,565		
Nbr of People	3	3	3	3				
Nbr of Days	3	3			3			
Total	1,251	639	1,500	120	0	2,565	0	PY 1
							6,257	PY 2
							6,257	Total

Purpose of Trip: SPIE Meeting
Depart From: Baltimore/Washington
Arrive To: San Francisco, CA

Trip 2

	Lodging	**MI&E or Per Diem**	**Airfare**	**Ground Trans**	**Auto Rental**	**Misc**	**Total**	
Rate	0	0	0	20	0	1,338		
Nbr of People	2	2	2	2				
Nbr of Days	3	3			3			
Total	0	0	0	40	0	1,338	0	PY 1
							1,419	PY 2
							1,419	Total

Purpose of Trip: AAS
Depart From: Greenbelt, MD
Arrive To: Washington DC

Summary of Travel Budget Requirements

Domestic/Foreign; Purpose	PY 1	PY 2	Total
Domestic; SPIE Meeting	0	6,257	6,257
Domestic; AAS	0	1,419	1,419
Total:	0	7,676	7,676

Other

Other Direct Costs, SED - These costs, as discussed in NASA financial regulations, are for services to support the research effort that go beyond the standard costs considered under Center Management and Operations (Center Overhead), and are not incurred elsewhere within GSFC. Within the Sciences and Exploration Directorate these costs cover system administration for the complex information technology services required to support the proposed research activities, administrative and resource analysis support, and supplies to support the research effort.

Facilities and Administrative (F&A) Costs, GSFC

NASA CM&O (Center Management and Operations) is managed from Headquarters and is therefore excluded from this proposal.

Description of Required Facilities and Equipment

Existing Facilities and Equipment for Which Funding is Not Requested

The existing facilities and equipment needed to carry out the proposed research are available at the PI's institution, NASA/Goddard Space Flight Center Code 660 Astrophysics Science Division. These include the VNC lab in Bld 34, Room C134A and the VNC testbed built by NASA/GSFC Code 667 and all the alignment and test equipment including a Zygo interferometer, theodolites, coordinate measuring machine, and custom deformable mirrors and their control systems. These facilities come at no cost to this effort as it was built up under past SAT and APRA work.

Budget Justification: Details

Below is the total budget for the items described in the Budget Narrative. Also below are any supporting budgets.

NOTE: For NASA ROSES proposals, NASA Civil Servant Labor is redacted per SMD guidance from NSPIRES and from budgets in Proposal Documents; NASA HQ will retrieve the full NASA budget for each NASA Center from the agreed-upon repository.

COMPETITION SENSITIVE - FOR PROPOSAL SUBMISSION & PANEL REVIEW ONLY
Budget by Program Year (NSPIRES)

Solicitation: NNH13ZDA001N-SAT Strategic Astrophysics Technology D.8
GSFC Proposer Name: RICHARD LYON
Proposal Number: 600-14-4125
Proposal Title: 600-14-4125 - Segmented Aperture Nulling Coronagraphy
Total Excluding GSFC CS Labor: 393342
Proposal Start Date: 10/01/2014
Proposal End Date: 09/30/2016

	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	Total FTE	Total Cost
A. Senior / Key Personnel (CS Only)						
Scientist-Tier 4	0.55	0	0.55	0	1.10	0
Engineer-Mid	0.30	0	0.27	0	0.57	0
Subtotal	0.85	0	0.82	0	1.67	0
B.1.a-c Other Personnel (Civil Servants Not Named as Co-I in Proposal)						
Technician-Mid	0.04	0	0.03	0	0.07	0
Subtotal	0.04	0	0.03	0	0.07	0
Subtotal GSFC Civil Servants	0.89	0	0.85	0	1.74	0
Other Personnel (Non-Civil Servants)						
B.2.a On-Site Contractors	0.50	90000	0.83	133488	1.33	223488
B.2.b On-Site Cooperative Agreements	0.00	0	0.00	0	0.00	0
B.2.c On-Site Test & Fab Pool	0.04	23640	0.03	16234	0.07	39874
C. Off-Site Subawards / Subcontracts	0.00	0	0.00	0	0.00	0
Subtotal Other Personnel	0.54	113640	0.86	149722	1.40	263362
Subtotal Labor Cost	1.43	113640	1.70	149722	3.14	263362
Others						
Equipment		0		0		0
Materials and Supplies		54100		15000		69100
Publications		0		0		0
Consultant Services		0		0		0
ADP/Computer Services		0		0		0
Rental/User Fees		0		0		0
Alterations and Renovations		0		0		0
Mission Design Center		0		0		0
Test Services Non GSFC		0		0		0
Fab Services Non GSFC		0		0		0
Other Costs		0		0		0
Subtotal Others		54100		15000		69100
Travel Total		0		7676		7676
Other Direct Costs SED		26196		27009		53205
Subtotal Other Cost		80296		49685		129981
Indirect CM&O		0		0		0
Total Proposal Costs	1.43	193936	1.70	199407	3.14	393342

Grand Total Proposal Costs

	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	Total FTE	Total Cost

Civil Servant GSFC	0.89	0	0.85	0	1.74	0
Contractor On-Site	0.54	113640	0.86	149722	1.40	263362
Subawards / Off-Site	0.00	0	0.00	0	0.00	0
Other Costs Direct		80296		49685		129981
Other Costs CM&O		0		0		0
Total Proposal Costs	1.43	193936	1.70	199407	3.14	393342

Funds Distribution

	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	Total FTE	Total Cost
Other NASA Centers and JPL	0.00	0	0.00	0	0.00	0
GSFC	1.43	193936	1.70	199407	3.14	393342
Total Proposal Costs	1.43	193936	1.70	199407	3.14	393342

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	FY 2015 FTE	FY 2015 Cost	FY 2016 FTE	FY 2016 Cost	FY 2017 FTE	FY 2017 Cost	Total FTE	Total Cost
A. Senior / Key Personnel (CS Only)								
Scientist-Tier 4	0.55	0	0.55	0	0.00	0	1.10	0
Engineer-Mid	0.30	0	0.27	0	0.00	0	0.57	0
Total	0.85	0	0.82	0	0.00	0	1.67	0
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Total	0.04	0	0.03	0	0.00	0	0.07	0
Subtotal GSFC Civil Servants	0.89	0	0.85	0	0.00	0	1.74	0
Other Personnel (Non-Civil Servants)								
B.2.a On-Site Contractors	0.50	90000	0.83	133488	0.00	0	1.33	223488
B.2.b On-Site Cooperative Agreements	0.00	0	0.00	0	0.00	0	0.00	0
B.2.c On-Site Test & Fab Pool	0.04	23640	0.03	16234	0.00	0	0.07	39874
C. Off-Site Subawards / Subcontracts	0.00	0	0.00	0	0.00	0	0.00	0
Subtotal Other Personnel	0.54	113640	0.86	149722	0.00	0	1.40	263362
Subtotal Labor Cost	1.43	113640	1.70	149722	0.00	0	3.14	263362
Others								
Equipment		0		0		0		0
Materials and Supplies		54100		15000		0		69100
Publications		0		0		0		0
Consultant Services		0		0		0		0
ADP/Computer Services		0		0		0		0
Rental/User Fees		0		0		0		0
Alterations and Renovations		0		0		0		0
Mission Design Center		0		0		0		0
Test Services Non GSFC		0		0		0		0
Fab Services Non GSFC		0		0		0		0
Other Costs		0		0		0		0
Subtotal Others		54100		15000		0		69100
Travel Total		0		7676		0		7676
Other Direct Costs SED		26196		27009		0		53205
Subtotal Other Cost		80296		49685		0		129981
Indirect CM&O		0		0		0		0
Total Proposal Costs	1.43	193936	1.70	199407	0.00	0	3.14	393342

Grand Total Proposal Costs

	FY 2015 FTE	FY 2015 Cost	FY 2016 FTE	FY 2016 Cost	FY 2017 FTE	FY 2017 Cost	Total FTE	Total Cost
Civil Servant GSFC	0.89	0	0.85	0	0.00	0	1.74	0
Contractor On-Site	0.54	113640	0.86	149722	0.00	0	1.40	263362
Subawards / Off-Site	0.00	0	0.00	0	0.00	0	0.00	0
Other Costs Direct		80296		49685		0		129981
Other Costs CM&O		0		0		0		0
Total Proposal Costs	1.43	193936	1.70	199407	0.00	0	3.14	393342

Funds Distribution

	FY 2015 FTE	FY 2015 Cost	FY 2016 FTE	FY 2016 Cost	FY 2017 FTE	FY 2017 Cost	Total FTE	Total Cost
Other NASA Centers and JPL	0.00	0	0.00	0	0.00	0	0.00	0
GSFC	1.43	193936	1.70	199407	0.00	0	3.14	393342
Total Proposal Costs	1.43	193936	1.70	199407	0.00	0	3.14	393342